Continuous room-temperature operation of microdisk laser diodes

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Abstract

InGaAs/GaAs/AlGaAs multiple quantum well microdisk laser diodes operate continuously at room-temperature. A threshold current of I_{th} = 1.2 mA is measured for a R = 4.75 μm radius disk with lasing emission wavelength near λ = 1.0 μm.

Microdisk lasers are attractive elements for future photonic circuits due to their small dimensions, low threshold current and in-plane emission characteristics. Conventional microdisk laser diodes, by virtue of their geometry, suffer from poor heat-sinking [1]. The challenge is to improve thermal design without incurring a significant penalty in the optical and electrical characteristics. Recently, continuous room-temperature operation of optically pumped microdisk lasers was reported using improved thermal management [2]. We report continuous room-temperature operation of electrically driven R = 4.75 μm radius InGaAs/GaAs/AlGaAs microdisk laser diodes with emission at wavelength $\lambda = 1.0$ μm.

Fig. 1(a) shows calculated temperature distribution in a R = 5 μm radius conventional microdisk laser supported on a r = 3.5 μm radius pedestal for a uniform injected heat power of 10 mW around the periphery of the active region. The periphery of the disk is 94 K above the substrate temperature. Fig. 1(b) shows for an Aluminum-oxide (AlO_y) encased microdisk laser the maximum temperature is only 20 K above the substrate temperature. In this device high vertical optical confinement is provided by the refractive index difference between semiconductor core ($n_{semi} = 3.5$) and AlO_y cladding ($n_{oxide} = 1.6$). The optical confinement factor for the AlO_y-encased device is estimated to be 0.136 as compared to 0.141 for a conventional microdisk laser. Fig. 1(c) shows a schematic of an AlO_y-encased microdisk laser similar to the one in Fig. 1(b) but with additional carrier confinement. An insulating current blocking layer present between the p-metal contact and the semiconductor leads to an absence of carrier injection in the middle of the disk. Fig. 1(c) also shows an scanning electron microscope (SEM) picture of a typical R = 4.75 μm, r = 3.25 μm, r' = 2.5 μm device reported in this work. For the device shown in Fig. 1(d), AlO_y in the middle of the disk acts as the current blocking layer.

The MOCVD-grown layer structure is shown in Table 1. After removal from the growth chamber, amorphous SiN_x is chemical vapor deposited at 325 °C on top of the epitaxial layer. Standard photolithography and dry etching are used to pattern the SiN_x layer. Electron Cyclotron Resonance (ECR) etching is used to define microdisk mesas. After removal of the SiN_x layer, wet thermal oxidation [3] is performed to convert 1.5 μm of $Al_{0.9}Ga_{0.1}As$ near the periphery of the etched microdisk into AlO_y. The 0.2 μm thick amorphous SiN_x, which acts as the current blocking layer, is chemical vapor deposited and p-metal contact is subsequently defined on the microdisk mesas using a lift-off technique. The semiconductor substrate is thinned to a thickness of 150 μm and backside n-metal contact is deposited. After rapid thermal annealing at 380 °C, the device is characterized.

Fig. 2 shows the measured light output L at the lasing wavelength, λ_0 = 1001 nm versus the continuous injected current I at room-temperature for a typical R = 4.75 μm and r = 3.25 μm AlO_y-encased microdisk with a r' = 2.5 μm radius current blocking layer seen in Fig. 1(c). A well-defined threshold is seen at an injection current, I_{th} = 1.2 mA. The threshold current of the device would be in the μA range if the perimeter of the microdisk was smoother and the exposed surfaces passivated. The measured spontaneous emission at λ_0 is r_{sp} and is shown on a twelve-times y-axis scale. The slight sublinear L-I characteristics above threshold is tentatively attributed to an increase in active region temperature with increasing I. Fig. 2 also shows optical spectra at an injection current (i) I = I_{th} = 1.2 mA where the resonance at λ_0 = 1001 nm is only 3 dB above the spontaneous emission background and (ii) I = 2.5 mA where the lasing resonance is 22 dB above the spontaneous emission background. The linewidth of the resonance is limited by the 1 nm resolution of the spectrometer. The ideality factor of the diode is 1.39 and the series resistance is 337 Ω.

Assuming lasing into the fundamental radial mode of index N = 1, the azimuthal number M of the whispering gallery resonance can be estimated using $M\lambda_0 = 2\pi R n_{eff}$ where n_{eff} is the effective refractive index in the vertical direction for the slab waveguide. Using n_{eff} = 3.11, we find that the device lases into the M = 93 resonance.

In conclusion, continuous room-temperature operation of R = 4.75 μm radius InGaAs/GaAs/AlGaAs microdisk laser diodes is achieved using improved electrical, optical, mechanical, and thermal design. Devices with threshold current I_{th} = 1.2 mA and lasing wavelength λ ~ 1.0 μm are demonstrated.

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References:

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Table 1:

MOCVD-grown layer structure used in this work.

Table 1:

Material	Thickness (nm)	Impurity concentration (cm^{-3})	x
$In_xGa_{1-x}As$	10	$p = 1 \times 10^{19}$	x = 0.1
GaAs	100	$p = (3\text{-}10) \times 10^{18}$	
$Al_xGa_{1-x}As$	50	$p = 3 \times 10^{18}$	x = 0.9 to 0.15
$Al_xGa_{1-x}As$	500	$p = 1 \times 10^{18}$	x = 0.9
$Al_xGa_{1-x}As$	20	$p = 8 \times 10^{17}$	x = 0.5 to 0.9
$Al_xGa_{1-x}As$	20	$p = 2 \times 10^{17}$	x = 0.5
$Al_xGa_{1-x}As$	20	i	x = 0.25
GaAs	20	i	
$In_xGa_{1-x}As$	80	i	x = 0.2
GaAs	15	i	
$In_xGa_{1-x}As$	8	i	x = 0.2
GaAs	15	i	
$In_xGa_{1-x}As$	8	i	x = 0.2
GaAs	20	i	
$Al_xGa_{1-x}As$	20	i	x = 0.25
$Al_xGa_{1-x}As$	20	$n = 2 \times 10^{17}$	x = 0.5
$Al_xGa_{1-x}As$	20	$n = 8 \times 10^{17}$	x = 0.9 to 0.5
$Al_xGa_{1-x}As$	500	$n = 1 \times 10^{18}$	x = 0.9
$Al_xGa_{1-x}As$	50	$n = 3 \times 10^{18}$	x = 0.15 to 0.9
GaAs	substrate	$n = 1 \times 10^{18}$	

Figure captions

Figure 1. (a) Temperature profile for P_{in} = 10 mW uniform heat injection around the periphery of the active region for a conventional microdisk laser with R = 5 µm and r = 3.5 µm. Constant temperature contours are plotted every 4 K. (b) Same as (a) but for an AlO_y-encased microdisk laser. Constant temperature contours are plotted every 1 K. (c) Schematic and SEM image of an AlO_y-encased microdisk laser with carrier confinement using 0.2 µm thick and r' = 2.5 µm radius current blocking layer reported in this work. (d) Schematic and SEM image of an AlO_y-encased microdisk laser with improved carrier confinement using AlO_y. The small arrows indicate carrier injection.

Figure 2. Measured room-temperature optical power at lasing wavelength λ_0 = 1001 nm versus continuous injected current for a typical R = 4.75 µm radius microdisk laser with a r' = 2.5 µm radius current blocking layer. The power in spontaneous emission background r_{sp} at the lasing line multiplied by a factor of 12 is also shown. Inset shows measured electrical characteristics of the diode. The ideality factor is measured to be 1.39 and the series resistance of the laser diode is 337 Ω. Measured room-temperature optical spectra at a continuous injection current (i) I = I_{th} = 1.2 mA and (ii) I = 2.5 mA is also shown.

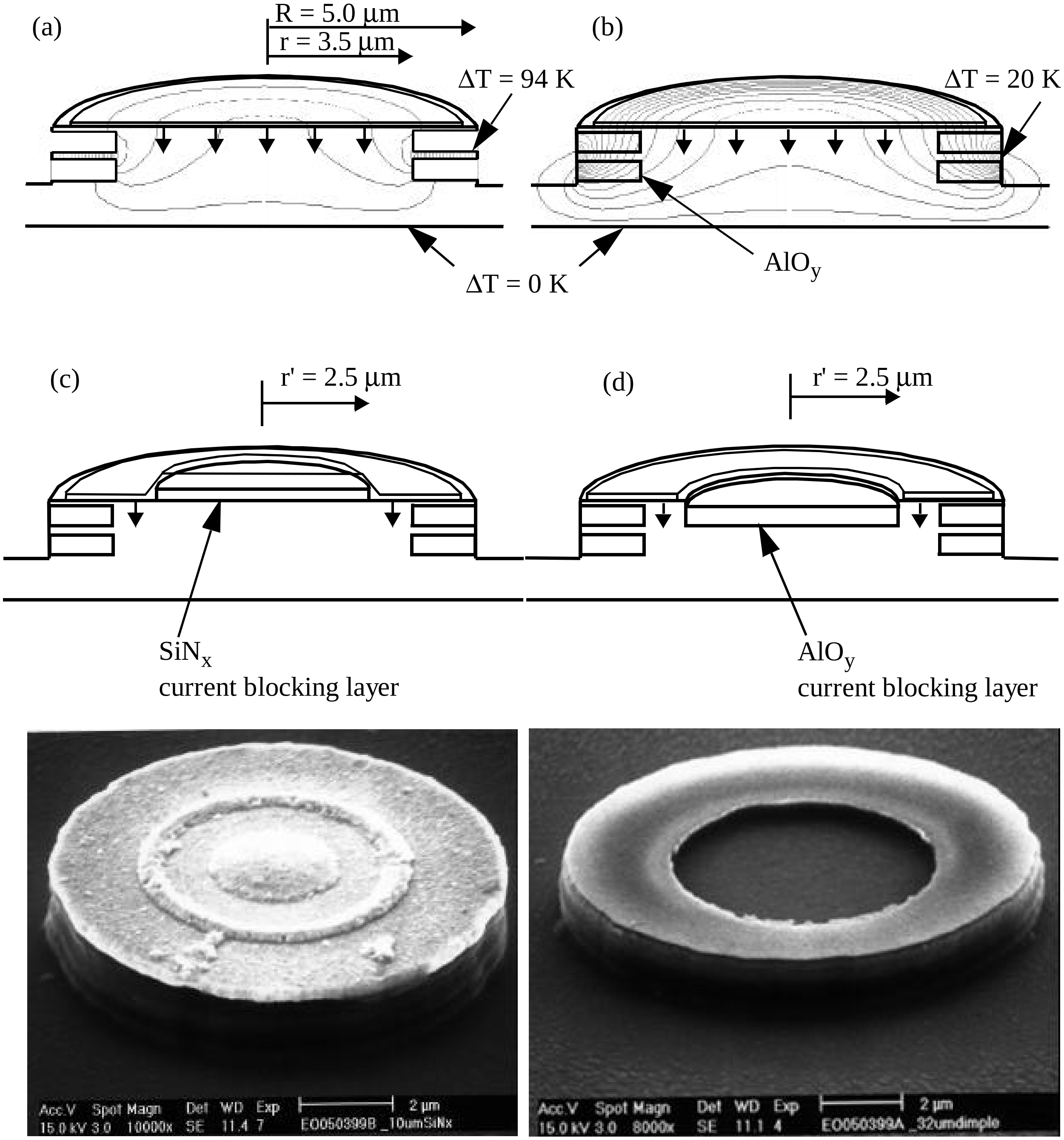
(a)
R = 5.0 µm
r = 3.5 µm
ΔT = 94 K
(b)
ΔT = 20 K
AlO$_y$
ΔT = 0 K
(c)
r' = 2.5 µm
(d)
r' = 2.5 µm
SiN$_x$ current blocking layer
AlO$_y$ current blocking layer
Acc.V Spot Magn Det WD Exp 2 µm
15.0 kV 3.0 10000x SE 11.4 7 EO050399B _10umSiNx
Acc.V Spot Magn Det WD Exp 2 µm
15.0 kV 3.0 8000x SE 11.1 4 EO050399A _32umdimple

Figure 1.

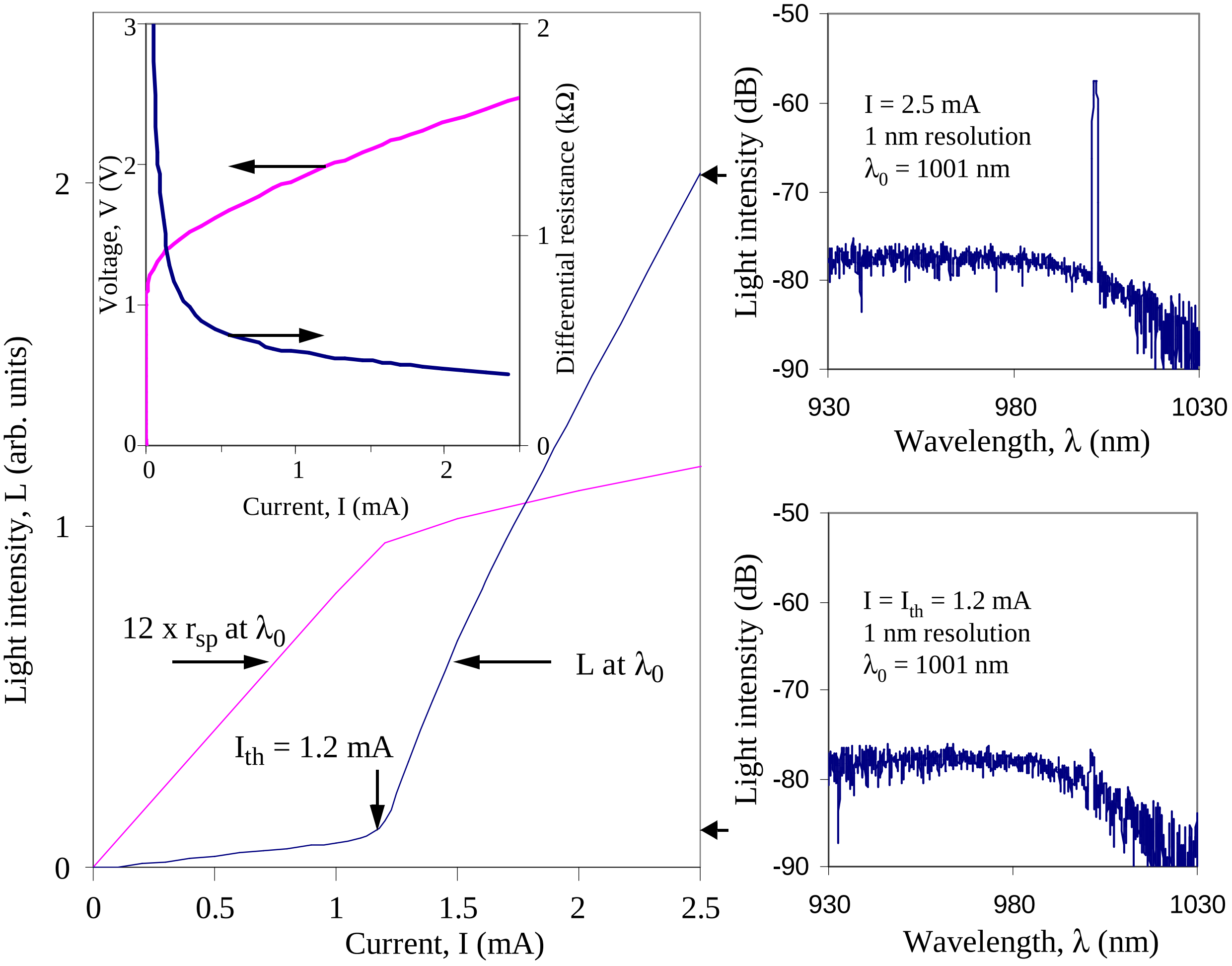
Light intensity, L (arb. units)
0
1
2
Current, I (mA)
0
0.5
1
1.5
2
2.5
12 x r_{sp} at λ_0
L at λ_0
I_{th} = 1.2 mA
Voltage, V (V)
Differential resistance (kΩ)
Current, I (mA)
3
2
1
0
0
1
2
Light intensity (dB)
-50
-60
-70
-80
-90
930
980
1030
Wavelength, λ (nm)
I = 2.5 mA
1 nm resolution
λ_0 = 1001 nm
Light intensity (dB)
-50
-60
-70
-80
-90
930
980
1030
Wavelength, λ (nm)
I = I_{th} = 1.2 mA
1 nm resolution
λ_0 = 1001 nm

Figure 2.